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LINE PROFILES AND INTENSITY RATIOS IN PROMINENCE MODELS WITH A PROMINENCE TO CORONA INTERFACE

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ABSTRACT

In this work we study the hydrogen, helium and calcium spectra emitted by a one-dimensional prominence model in magneto-hydrostatic equilibrium. The prominence slab consists of two parts: a cool core where the plasma is optically thick for some lines, and a prominence-to-corona transition region (PCTR) with a strong temperature gradient. The models are defined by 5 parameters: temperature, pressure, slab thickness, microturbulent velocity and altitude. We solve the NLTE radiative transfer equations for all optically thick transitions. We present line ratios between infrared, optical and EUV lines, as well as line profiles.
We show that the presence of a PCTR, where both collisional and radiative excitations are important, affects H, He, and Ca populations and emergent lines in different manners.

Key words: Sun: prominences; radiative transfer; Line: profiles; Line: formation.

1. INTRODUCTION

Prominences are cool, dense plasma clouds embedded in the solar corona as seen at the solar limb. They are illuminated by a strong chromospheric and coronal radiation which can penetrate the structure and excite the prominence plasma, the latter being consequently out of Local Thermodynamic Equilibrium (LTE). The line formation in 1D prominence models has been studied for several elements by several authors, following different strategies (e.g. Gouttebroze & Heinzel, 2002; Labrosse & Gouttebroze, 2001; Gouttebroze & Labrosse, 2000; Anzer & Heinzel, 1999; Fontenla et al., 1996; Morozhenko, 1984; Yakovkin et al., 1982; Heasley & Milkey, 1978). In our approach we define 5 parameters, namely the temperature, the pressure, the microturbulent velocity of the prominence plasma, the altitude and the thickness of the prominence slab. This slab stands vertically above the solar surface. Its height defines the dilution factor for the incident radiation which takes into account the center-to-limb variations for hydrogen lines with upper level $n \lesssim 5$.
Simple models with constant temperature and pressure can well reproduce the spectral features of most observed lines, and give us a good understanding of these structures, as long as **a)** we take properly into account the detailed frequency-dependent incident radiation for the principal atomic transitions (this radiation is indeed used as a boundary condition for the resolution of the radiative transfer equations); **b)** the partial redistribution in frequency (PRD) is considered for the main resonance lines. However, observations show that prominences are not isothermal, and there is an interface between the relatively cool core of the prominence body and the hot surrounding corona. This interface has to be taken into account in the modelling in order to match observations from UV to infrared lines at once.
In the second section we briefly describe how the computations are carried out. Then we present the type of models that are used in this work. The effect of the structure of the PCTR on the emitted intensities is studied in section 4.

2. COMPUTATIONAL METHOD

Here we consider the formation of hydrogen, helium and calcium lines in the frame of one-dimensional models in magnetohydrostatic equilibrium. Computations are made in two steps. **1)** We solve the ionization equilibrium for hydrogen (20 bound levels), then the statistical equilibrium (SE) and radiative transfer (RT) equations. We thus obtain the electron densities, hydrogen level populations out of LTE, and the radiation due to hydrogen. **2)** We solve SE and RT equations for helium (29 bound levels for He I, 4 for He II) and for calcium (1 level for Ca I, 5 for Ca II) independently, taking into account the electron densities and internal radiation due to hydrogen obtained from 1). This leads to the non-LTE level populations and we finally calculate the emitted spectra from these two elements. SUMER ob-

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servations from Warren et al. (1998) are used for the incident radiation of Lyman lines 2 to 8. We also use detailed incident profiles for Lyα and the Ca II lines (see Gouttebroze et al., 1997) and the resonance lines of He I (at 584 and 537 Å) and He II (304 Å) as in Labrosse & Gouttebroze (2001). Partial frequency redistribution is considered for the H I Lyα and Lyβ, He I 584 Å and He II 304 Å, and the Ca II H and K optically thick EUV resonance lines. More details on the method and on the atomic models can be found in Gouttebroze & Labrosse (2000) for hydrogen, Labrosse & Gouttebroze (2001) for helium, and Gouttebroze & Heinzel (2002) for calcium.

3. MODELS

Anzer & Heinzel (1999) have recently studied the energy balance in one-dimensional models of solar quiescent prominences in magneto-hydrostatic equilibrium. We have adopted their models for the pressure and temperature variations in the inner part of the prominence, which consists in a cool core surrounded by the cool part of the transition region. The pressure profile is given by

$$p(m) = 4p_c \frac{m}{M}\left(1 - \frac{m}{M}\right) + p_0 ,$$

where m is the column mass, p_0 is the coronal pressure at the outer boundary, and $p_c = p_{\rm cen} - p_0$, with $p_{\rm cen}$ the central gas pressure. Anzer & Heinzel (1999) also suggested a functional dependence of the temperature on the column mass m:

$$T(m) = T_{\rm cen} + (T_{\rm tr} - T_{\rm cen})\left[1 - 4\frac{m}{M}\left(1 - \frac{m}{M}\right)\right]^{\gamma} ,$$

where $T_{\rm cen}$ and $T_{\rm tr}$ are the temperatures at the centre of the slab and at the outer boundary respectively, and γ is a free parameter ($\gamma \geq 2$).
For this work we have computed 9 different models with a PCTR, and 1 isothermal and isobaric model which will serve as a reference model. All parameters are listed in Table 1. With the combination of these different models, we investigate the effects of the parameters γ, $P_{\rm cen}$, and $T_{\rm tr}$ on the emitted spectra.

Table 1. Model parameters used in this work. Model 1 is isothermal and isobaric. All other models have a PCTR. In all PCTR models, the coronal pressure $p_0 = 2\ 10^{-2}$ dyn cm^{-2}, the central temperature $T_{\rm cen} = 8000$ K, the total column mass $M = 1.8\ 10^{-5}$ g cm^{-2}, the altitude $H = 20\,000$ km, and the microturbulent velocity $V = 5$ km s^{-1}.

Model	$P_{\rm cen}$ (dyn cm^{-2})	$T_{\rm tr}$ (K)	γ
1	0.02	8000	-
2	0.10	30000	3
3	0.10	30000	12
4	0.10	30000	30
5	0.10	50000	30
6	0.10	80000	30
7	0.02	30000	30
8	0.05	30000	30
9	0.20	30000	30
10	0.50	30000	30

4. STRUCTURE OF THE PCTR

4.1. Temperature gradient

Here we use models 1 to 4 to study the effect of the value of γ. Increasing this parameter increases the steepness of the temperature gradient. The emerging profiles are shown in Fig 1. For all the hydrogen lines studied, the intensity decreases when the slope of the temperature gradient increases. In low γ cases, the region where the resonance lines are formed is more extended. Helium line intensities also decrease with the slope of the temperature gradient. Concerning the optically thin line at 10830 Å, the temperature gradient has almost no effect on the profile: this line is formed in the cold slab centre. An interesting feature of the Ca II lines is that their intensities increase when the temperature gradient becomes steeper in the PCTR. In that case the Ca III/Ca II population ratio decreases at slab centre.

4.2. Central pressure

We now use model 1 for the isothermal isobaric reference, and then models 6 to 10 to observe the effect of increasing the central pressure. We show the half emergent profiles for the Lyα, He I 10830 Å and Ca II K lines in figure 2. All the hydrogen lines have higher intensities when the central pressure is increased. The Lyα line profile keeps its central reversal, but higher Lyman lines do not show any self-reversal. The resonance lines of helium are poorly affected by the change of the central pressure, due to their great optical thickness and to a decrease of the penetration of the exciting and ionizing EUV continuum. It is interesting to note that the optically thin triplet line sees its intensity notably decreased with the pressure. This behaviour is different from the case of isothermal and isobaric slabs studied by Labrosse & Gouttebroze (2001). The presence of a PCTR affects the population mechanisms of the helium energy levels. Finally, the central pressure increase raises the emitted intensities of all Ca II lines. The Ca III/Ca II population ratio at slab centre is reduced with increasing central pressure.
In Fig. 3 we focus on the ratio E(D3)/E(Hβ) as a function of E(Hβ) (left panel) and of the pressure (right panel). This ratio has been both observed and theoretically studied for many years. Some references of observations are given in Gouttebroze et al. (2002). In this paper the authors showed that computed ratios are close to the observations when one considers several slabs along the line-of-sight (*com-*

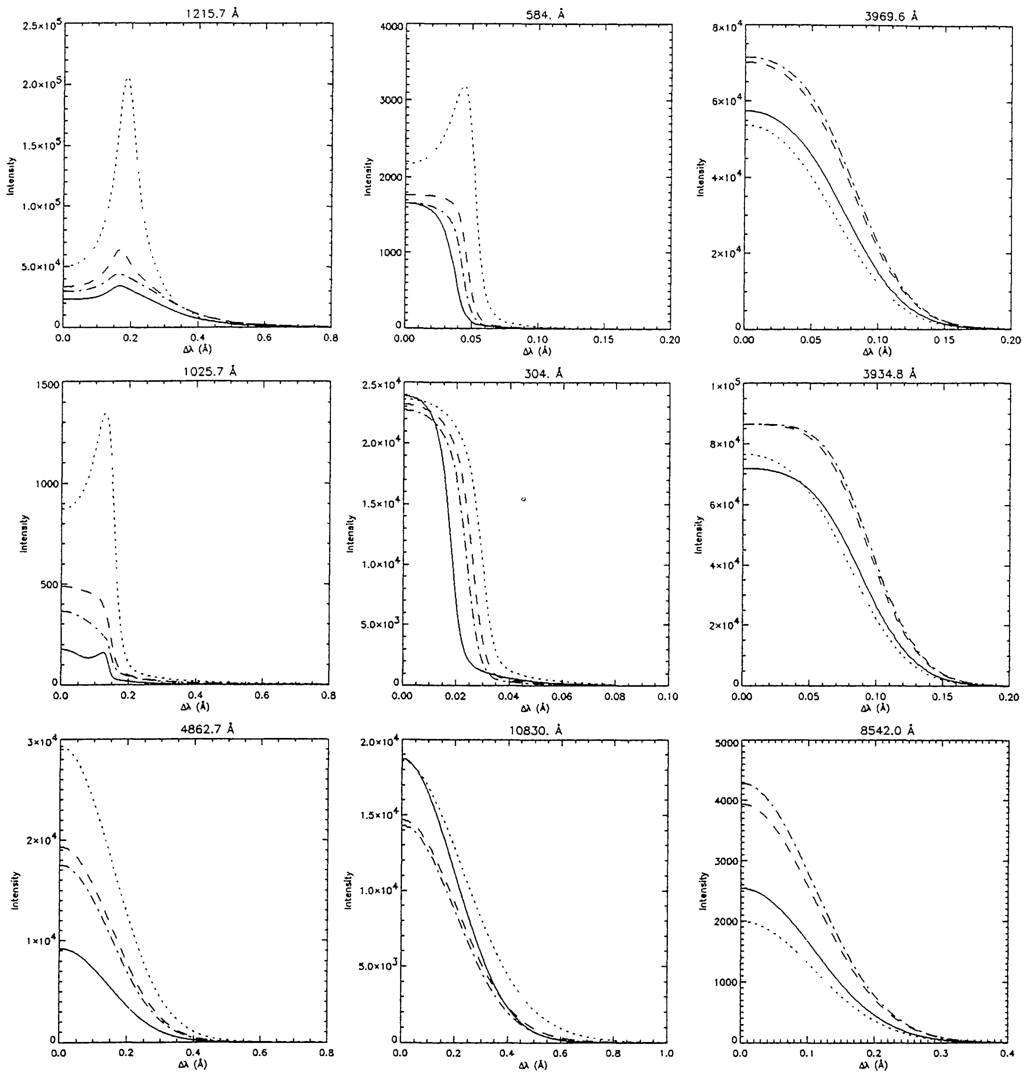

Figure 1. Half-emergent profiles for H, He, and Ca II lines when varying the temperature gradient. Left column, from top to bottom: hydrogen Lyα, Lyβ and Hβ lines; middle: He I 584, He II 304 and He I 10830 Å; right: Ca II H, Ca II K, Ca II 8542 Å. Solid line: model 1; dotted: model 2; dashed: model 3; dash/dots: model 4. Intensities are in erg s^{-1} sr^{-1} cm^{-2} $Å^{-1}$

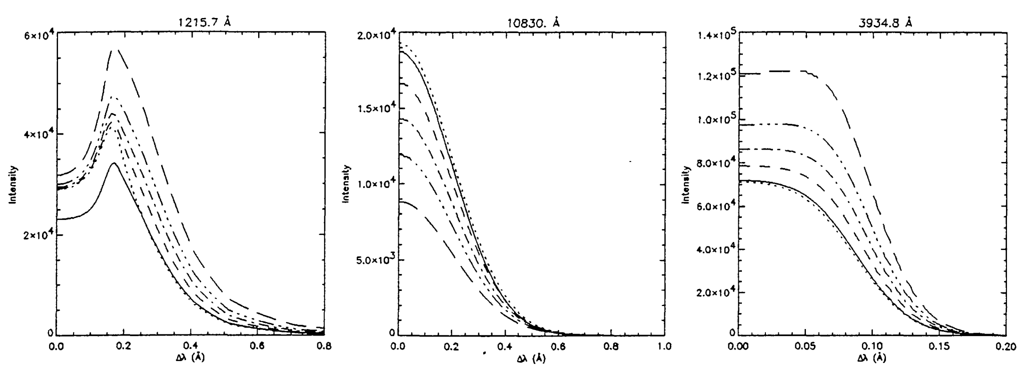

Figure 2. Half-emergent profiles for H, He, and Ca II lines when varying the central pressure. From left to right: hydrogen Lyα, He I 10830 Å, Ca II K. Solid line: model 1; dotted: model 7; dashed: model 8; dash/dot: model 6; dash/three dots: model 9; long dashes: model 10. Intensities are in erg s^{-1} sr^{-1} cm^{-2} $Å^{-1}$

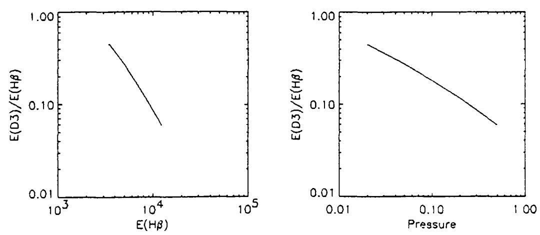

Figure 3. Computed ratio $E(D3)/E(H\beta)$ as a function of $E(H\beta)$ (left panel) and of the central gas pressure (right panel).

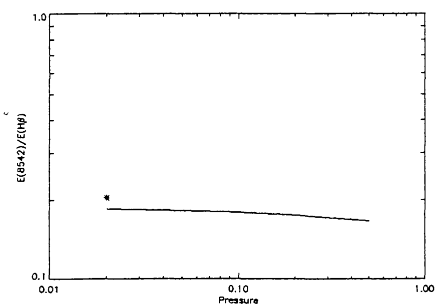

Figure 4. Computed ratio $E(Ca\,II\ 8542)/E(H\beta)$ as a function of the central gas pressure for models 6 to 10 (solid line). The star gives the value for model 1.

posite models). The obtained values in the present work are in the same range as their results from *monolithic* (one slab only) models, which are not able to match the observed ratios. We confirm that the ratio E(D3)/E(Hβ) is decreasing with the pressure. Gouttebroze & Heinzel (2002) revisited the formation of Ca II lines in isothermal isobaric model prominences. They concluded that the ratio E(8542)/E(Hβ) tends to decrease with pressure at high temperatures. This is consistent with our figure 4: the ratio slightly decreases for pressures greater than 0.1 dyn cm^{-2} . This is an effect of the Ca II to Ca III ionization in the transition region of the prominence (see also Gouttebroze et al., 2002).

4.3. Temperature at the outer boundary

To study the effect of the temperature at the outer boundary T_{tr} we have used model 1 for the isothermal isobaric reference, together with models 4 to 6. In order to save space the line profiles are not shown here. The intensities of the hydrogen Lyman lines increase when the transition region temperature increases. The Hβ line is not affected by the variation of the external temperature, which can be understood by the fact that this line is formed in the cool core of the prominence. The helium resonance lines do not show a great sensitivity to the temperature in the transition region in this type of model. As with the Hβ line, the optically thin line at 10830 Å is not sensitive to the temperature in the transition region. But unlike Hβ, its intensity decreases as compared to the isothermal isobaric reference model. This is related to the ionization of helium. The Ca II lines are not sensitive to the temperature at the surface of the PCTR, and as with hydrogen lines, their intensities are increased relatively to model 1. As shown by Gouttebroze & Heinzel (2002), the influence of hydrogen Lyman lines on Ca II to Ca III ionization is primordial.

5. DISCUSSION AND CONCLUSIONS

The presence of a PCTR affects hydrogen, helium and calcium populations in different manners. The structure of the PCTR has different effects on the H, He and Ca II lines, mainly depending on their optical thickness and on their temperature of formation, and also on the degree of ionization of these elements. These preliminary results promise to be very helpful in the interpretation of observed line profiles.

In a future work we will compare our computed helium line profiles of EUV resonance lines with high spectral resolution observations from SUMER, and see if the effect of the PCTR on the reversal at the centre of the 584 Å line can be observed. This numerical code can be used as a diagnostic tool for quiescent prominences when several lines are observed at the same time and at the same position in the structure.

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